

# NASA'S SUBSONIC JET TRANSPORT NOISE REDUCTION RESEARCH

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## Abstract

*Although new jet transport airplanes in today's fleet are considerably quieter than the first jet transports introduced about 40 years ago, airport community noise continues to be an important environmental issue. NASA's Advanced Subsonic Transport (AST) Noise Reduction program was begun in 1994 as a seven-year effort to develop technology to reduce jet transport noise 10 dB relative to 1992 technology. This program provides for reductions in engine source noise, improvements in nacelle acoustic treatments, reductions in the noise generated by the airframe, and improvements in the way airplanes are operated in the airport environs. These noise reduction efforts will terminate at the end of 2001 and it appears that the objective will be met. However, because of an anticipated 3–8% growth in passenger and cargo operations well into the 21st Century and the slow introduction of new the noise reduction technology into the fleet, world aircraft noise impact will remain essentially constant until about 2020 to 2030 and thereafter begin to rise. Therefore NASA has begun planning with the Federal Aviation Administration, industry, universities and environmental interest groups in the USA for a new noise reduction initiative to provide technology for significant further reductions.*

## 1 Introduction

Although new jet transport airplanes in today's fleet are considerably quieter than the first jet transports introduced about 40 years ago, airport community noise continues to be an important

national and international environmental issue. This is caused, not only by the tremendous growth in passenger and cargo operations over the past four decades, but also by a general increase in public interest and sensitivity to noise. This issue, if not adequately addressed, will continue to limit capacity and constrain the natural growth of the air transportation system.

NASA's interest and research in aircraft noise began over 50 years ago by its predecessor, the National Advisory Committee on Aeronautics (NACA), with pioneering research on airplane propeller noise. Figure 1 is a photograph of a P-51 Mustang fighter airplane which was used in NACA tests in the late 1940's to determine the effects of different tip shapes on propeller noise. A microphone, which was used to measure the noise in the plane of the propeller, is shown mounted on a sting inserted into a machine gun mount.



Figure 1. Early NACA propeller noise test on a P-51 fighter airplane.

Over this past 50 years, NASA has sponsored and conducted much of the research in understanding, predicting and reducing aircraft noise and its impact on community residents. In many cases this research was conducted in joint programs with the Federal Aviation Administration (FAA), Department of Defense, the nation's engine and airframe industry and universities. Although there have been programs addressing nearly all aircraft types, a significant amount of NASA's noise research efforts in recent years has focussed on conventional jet transport airplanes. The Advanced Subsonic Transport (AST) Noise Reduction program was begun in 1994 as a seven-year effort to develop technology to reduce aircraft noise 10 dB relative to 1992 technology. Although most of this reduction would come from reductions in engine source noise and improvements in nacelle acoustic treatments, reductions in the noise generated by the airframe itself would also be necessary. It was also realized that community noise impact could be reduced through improvements in the way airplanes are operated in the airport environs if advances in air traffic management and avionics were fully utilized.

The purpose of this paper is to describe the scope and progress of the NASA AST Noise Reduction program and to outline NASA's plans for future jet transport noise research.

## 2 History of Jet Transport Noise Reduction

When normalized on total engine thrust, today's new jet transport airplanes are about 20 decibels (dB) quieter than those introduced in the 1950's. This is generally perceived by people as being about one-fourth as noisy. Figure 2, courtesy of Boeing, indicates sideline noise levels of aircraft as related to the year they were introduced into service. The data have been normalized to 100,000 lb. thrust. This reduction resulted from major engine cycle changes, which greatly improved fuel efficiency, as well as incremental noise reduction efforts, which required careful optimization to prevent degradation in thrust and efficiency. In early turbojet engines, the high-velocity jet exhaust, mixing with the surrounding air, was the major noise source. In the 1960's, low-bypass-ratio turbofan engines were introduced that provided greater propulsive efficiency and less noise than the turbojets. The engine core and fan exhausts were combined and internally mixed, thereby lowering jet exhaust velocity with a significant reduction in jet exhaust noise. An even greater reduction in jet exhaust noise was achieved with the introduction of wide-bodied transports and second-generation turbofan engines with even higher bypass-ratios. However, with the jet exhaust no longer the primary noise source, further improvements in total engine noise required reduction in the fan-generated noise as

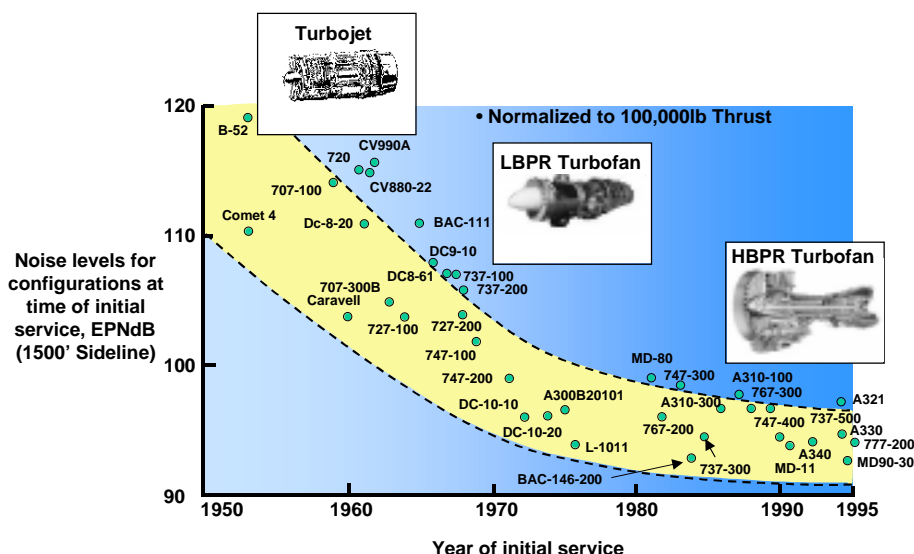


Figure 2. Normalized noise levels of transport aircraft by year of entry into service.

well as the jet noise. Most of the required fan noise reduction was achieved through elimination of inlet guide vanes, reduction in the number and rotational speed of fan blades, and improved blade aerodynamic design. A noise reduction breakthrough of particular importance was the fan blade passage frequency (BPF) “cut-off” design concept in which, with the appropriate selection of the number of fan and stator blades, the BPF tone does not propagate outside of the engine nacelle. Advances were also made in liners within engine nacelles so that the acoustic treatments could be designed or tuned for enhanced absorption of the fan tones.

### 3 Jet Engine Noise Reduction

Figure 3 indicates the noise sources and noise control elements in a modern high bypass-ratio turbofan jet engine. The principal noise sources are associated with the jet exhaust and fan. Secondary sources, due to the internal combustor and turbine stages, typically produce less sound power and contribute little to the overall radiated noise. Noise reduction approaches are to control the noise at its source by designing in noise control features and to absorb the sound generated by the source with acoustic liners.

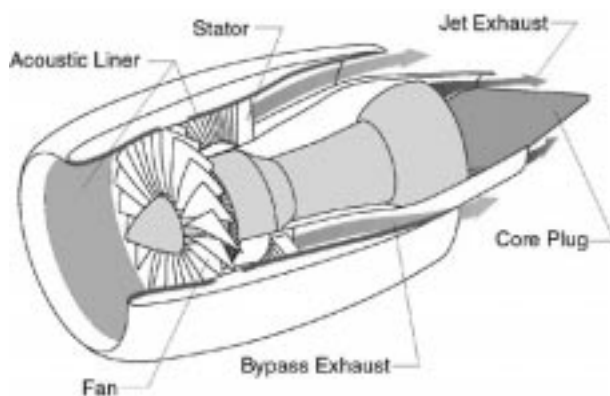


Figure 3. Noise sources and noise control elements in a modern high bypass-ratio turbofan jet engine.

#### 3.1 Jet noise

Mixing of the jet core and bypass exhausts and mixing with the atmosphere produce a very broad, haystack-shaped sound frequency spectrum. The shape of the spectrum reflects the fact that the eddies that comprise the turbulent mixing process vary considerably, increasing in size progressively downstream of the exhaust nozzle and decaying in intensity as the average exhaust velocity falls and the mixing becomes complete. Jet mixing noise is a strong function of jet exhaust velocity. Consequently, noise reduction strategies are aimed at increasing bypass ratio to lower nozzle exit velocities, and designing bypass and core flows to improve mixing with each other and the atmosphere. If the jet exhaust velocity is greater than the local speed of sound, very high levels of broadband shock-associated noise and screech tones can be generated. However these noises are usually controlled by careful design of the jet nozzles.

Over the past decade, and particularly during the AST Noise Reduction program, computational fluid dynamics (CFD) and an enlarged acoustic database for fan and core test model geometries has greatly improved the understanding of jet mixing noise. Unsteady three-dimensional computations have allowed the examination of the effects of mechanical mixing devices on exhaust velocity decay and turbulent kinetic energy. In the AST Noise Reduction program many different configurations and mixing devices have been tested at model scale [1]. Examples of configurations of a baseline nozzle and a noise reduction concept nozzle and are shown in figure 4. One-third octave spectra of noise levels projected to full scale at the 1500 ft sideline certification measurement location are also shown. As is typical of mechanical mixing devices, low frequency noise is reduced but high frequency noise is increased. Since high frequency noise is attenuated more by the atmosphere than low frequency noise, at 1500 ft and greater distances the high frequency noise increase contributes very little to the time- and

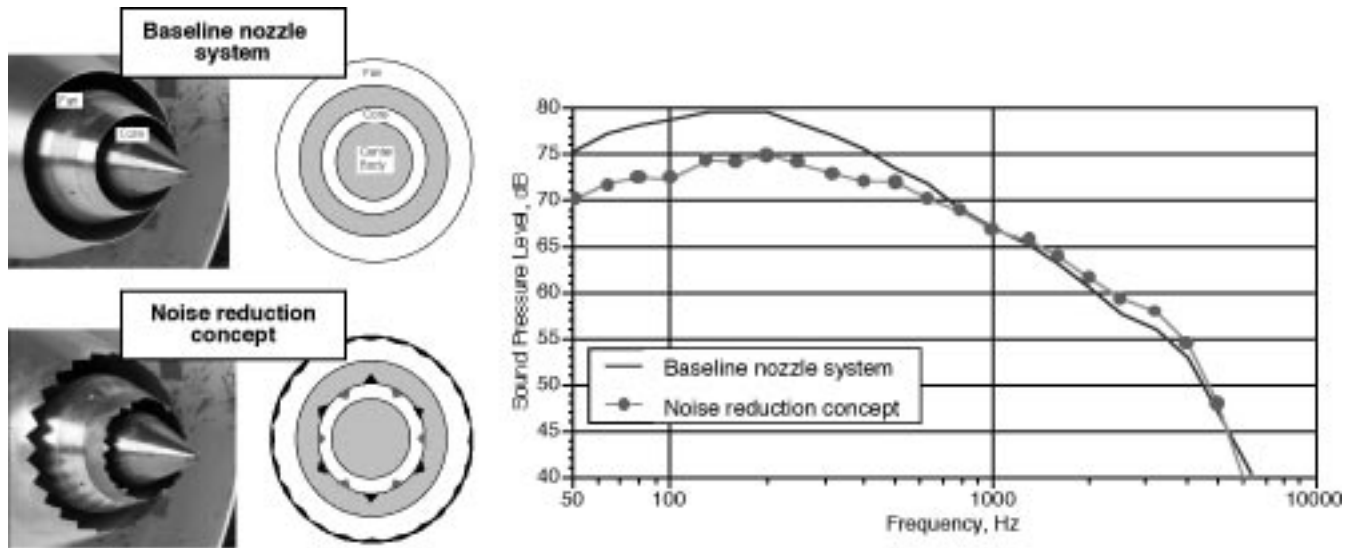


Figure 4. Examples of baseline and noise reduction concept separate flow nozzles and noise spectra.

frequency-integrated certification noise levels or human annoyance.

In other noise research projects, non-axisymmetric fan nozzles, offset centerline fan and core nozzles, multi-lobed core and fan nozzles, and the use of other mixing devices have been shown experimentally to effect the mixing process, and hence, the far field noise. In addition, a variety of internal and external core plugs have been investigated for various bypass ratio nozzles. Frequently it is found that jet noise reduction measures have significant adverse effects on performance and it is necessary to assess tradeoffs between noise reduction benefits and any performance penalties.

### 3.2 Fan noise

All fan noise is related to flow inhomogeneities interacting with surfaces. These are either inflow distortions being cut by the rotating fan blades, blade wakes sweeping across outlet guide vanes (stators), or turbulence passing near the blades or stators. The dominant source of fan tone noise is usually rotor-stator interaction, while broadband noise is due to turbulence. The turbulence may be from the duct boundary

layer, the blade wakes, or the blade tip vortices. In flight, small-scale turbulence in the inflow is quite small and not an important source of noise. Turbofan engines on modern commercial transport aircraft use acoustically lined inlets and fan exhaust ducts to suppress fan and other internally generated turbomachinery noise.

Research supported by the AST Noise Reduction program has produced improved computer codes to predict fan noise generation, propagation through the engine ducts, and radiation into the farfield. Unsteady CFD codes have been used to model tone noise generation. A new class of modeling called “Computational Aeroacoustics” has been developed recognizing the need for numerical approaches that predict both the flowfield and the noise. Propagation codes have been improved to incorporate realistic flow conditions and duct geometry. Radiation codes now employ advanced mathematical and computational formulations that greatly improve calculation efficiency [2]. An example that required just a few minutes of time on a personal computer is shown in figure 5. The left side of the figure shows the cross-section of the instantaneous acoustic pressure field in the plane of the fan and axially inside the duct. The structure of the “spinning modes” is clearly evident. The right side of the figure



shows the instantaneous acoustic pressure field as it radiates from the inlet and outlet of the duct.

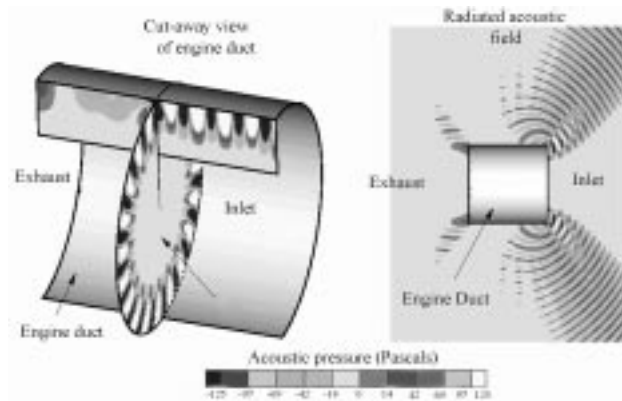


Figure 5. Computational aeroacoustic prediction of acoustic fields inside and radiated from a turbofan engine duct with no acoustic treatment.

Noise generation models have also been recently used to design configurations that reduce the noise produced by wakes from the fan blade sweeping across the stators. An example of a swept and leaned stator that was found to produce significantly lower tone and broadband noise levels in model fan noise



Figure 6. Model-scale swept and leaned stator used in wind tunnel acoustic tests shown with fan and without nacelle

experiments in shown in figure 6. Such concepts are also being examined in full-scale engine tests over a wide operating range.

### 2.3 Nacelles and liners

Propagation codes have been recently used to predict and model and full-scale tests have verified the acoustic benefits of shaping nacelle inlets to reduce noise below the aircraft. These shaped or “scarfed” inlets have protruding lower lips that reflect more of the fan noise up than do symmetric inlets.

Duct liner research has produced advances in predicting and measuring nacelle liner characteristics that have allowed optimized liner designs. New hardware and data processing techniques allow liner absorption measurement at high subsonic grazing flow speeds and frequencies up to 20kHz. This measurement capability is essential in interpreting model liner test results and in validating liner absorption prediction models. Three-dimensional aeroacoustic codes are being developed to account for flow in the duct and variable surface impedance of the duct liners [3]. Unsteady CFD codes are being used to incorporate perforate hole geometry and boundary layer characteristics into absorption prediction models. Concepts for adaptively adjusting liner properties in flight to maximize suppression at multiple operating points have also been explored, and parallel element liners, variable depth liners, and multi-layer liners show promise in increasing the broadband performance of passive liners.

Active noise cancellation technology is also being developed for controlling fan tones. Most of the work has been done on model-scale fan rigs where the effort has been focused on the noise generation process. Although there has been some success, further work in this area is needed.

Another duct liner treatment concept uses a new adaptation [4] of a very old concept of optical and acoustical interference. Figure 7 shows the concept and data from the installation of arrays of Herschel-Quincke tubes in the duct sidewall of a JT15D turbofan engine. Over a

fairly broad range of frequencies about the design point, the installation of two rows of tubes provided reductions of 4 dB to 8 dB in total acoustic power radiated in the forward direction from the inlet.

### 3 Airframe noise reduction

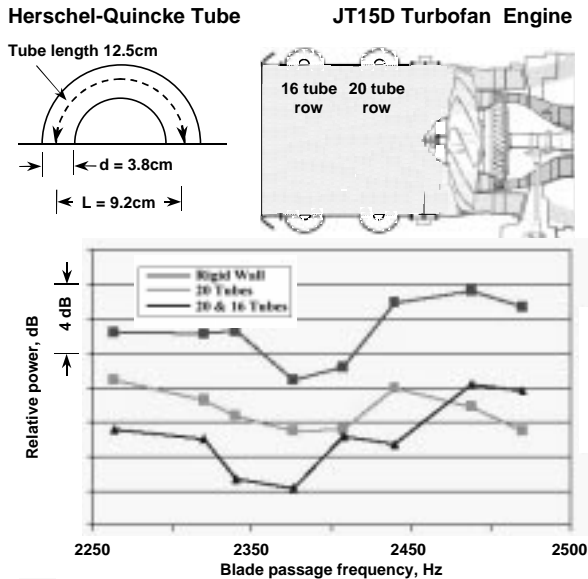


Figure 7. Application of Herschel-Quincke tubes for control of turbofan inlet noise.

In the early 1970's, it became evident that reduction of aircraft noise levels could not be achieved by further decreases in propulsion noise alone. Airframe noise was thought to be a lower limit or the ultimate noise barrier. Flyover noise measurements were performed on configurations that varied from gliders to large transport jets at reduced power settings. Empirical schemes were developed that could predict overall sound levels, spectra, and directivity reasonably well based on aircraft velocity, wing area, and simple geometric descriptions of those components suspected of being the main contributors. The primary noise sources on landing approach as indicated in figure 8, landing gear, flaps, and leading edge slats were generally known but the physics of the generation mechanisms was not fully understood.

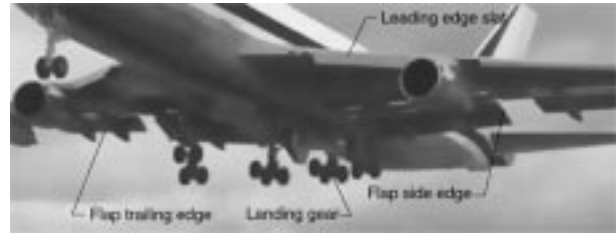


Figure 8. Airframe noise sources.

A more systematic approach to develop a better understanding of airframe noise was started in the early 1990's. This involved computing the steady flowfield surrounding key aircraft component structures that might develop the strong unsteadiness required for noise production and performing carefully controlled scale model tests [5]. Flap side-edge and leading-edge slat model scale components were fabricated and mean flowfield measurements were made to complement the computations. Large-scale coherent fluctuations were found to dominate the flowfield, which contained complex, vortical, separated flows. Placement of unsteady pressure transducers on subsequent component test models was guided by unsteady flow computations that predicted locations of strong fluctuations. In a series of flap side-edge experiments, figure 9, unsteady surface pressures were highly correlated with off-surface microphone measurements, corroborating that noise generation resulted from fluctuations in the large-scale fluid structures. Simultaneous advancements in phased microphone arrays and particle image velocimetry have identified the important local noise producing regions on model aircraft components. These computational and measurement technology advances allow key features of source noise spectra to be related to geometric features—a requirement for developing effective noise reduction concepts. Initial efforts at simple noise reduction designs for both the flap side-edge and leading-edge slat have proven successful at model scale. The focus of the airframe noise research is now shifting to the landing gear, perhaps the most complex of all airframe noise sources.

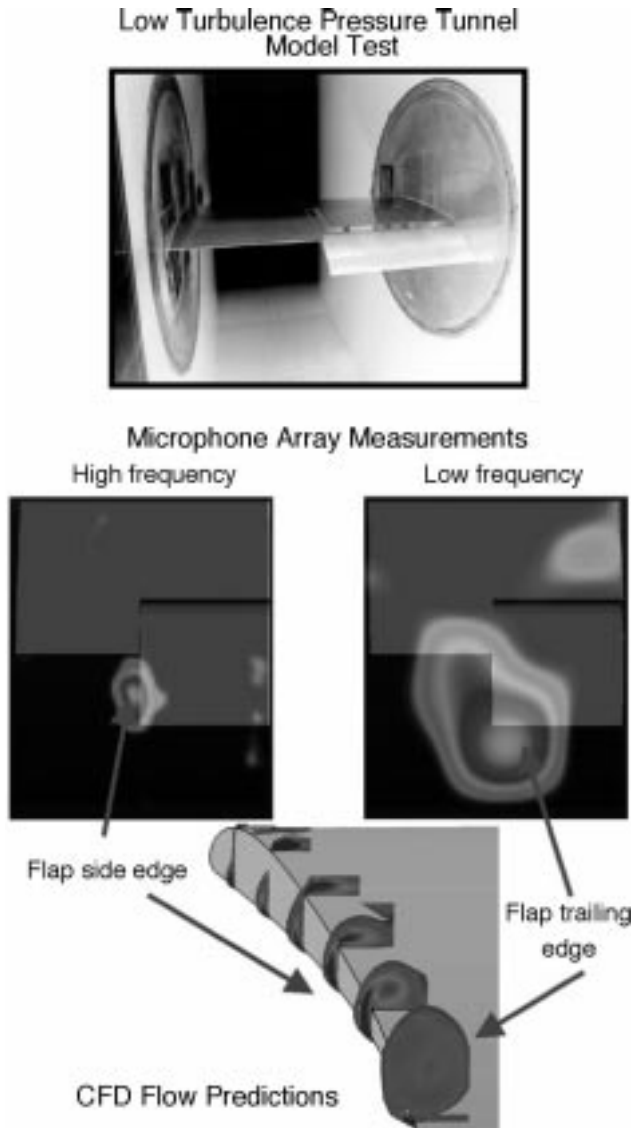


Figure 9. Experimental verification of predictions of flap side-edge noise source mechanism and locations.

#### 4 Airport operational noise impact reduction

Noise abatement flight procedures are used today at many airports to reduce the noise exposure in inhabited communities. These procedures include cutback in power during takeoff and rudimentary management of ground tracks to reduce flights over areas with high density populations. An airline may have one or a few standardized cutback procedures, which are consistent with flight safety and which can be used at specific airports. Such procedures can reduce noise levels in communities very near the airport, but communities at further

distances may experience higher noise levels than if power had been maintained and the aircraft were at higher altitude over the remote communities. Aircraft are routinely routed over bodies of water or other areas with little or no population to reduce total noise impact around an airport. The routing of airplanes up and down the Potomac River for takeoffs and landings at Ronald Reagan Washington National Airport is but one example. However traffic and weather condition at many airports frequently dictate runway usage and ground tracks with more than minimum impact. Weather conditions can shift noise exposure patterns from directly underneath the flight path so that adjacent communities can be inadvertently exposed to significantly greater noise than anticipated.

Because of the advances in on-board communication, navigation and surveillance (CNS) systems, differential global positioning systems (DGPS) and advanced air traffic management (ATM) systems, there exists the potential for significant reductions in noise impact in communities near airports. CNS systems in some recent airplanes can be programmed for flight profile and thrust management so that optimized noise abatement flight profiles could be tailored for individual airports and runways without excessive pilot workload. Such systems, actively coupled with DGPS, could provide for minimized noise impact for all routine departures.

Aircraft nominally approach runways on a 3-degree glideslope, particularly, during adverse weather conditions. They usually enter the Instrument Landing System (ILS) flight path from an altitude below the intended 3-degree slope several miles from the runway threshold. Consequently, areas further out from the airport are frequently exposed to noise levels greater than necessary. Also in order to maintain the prescribed glide slope, it is frequently necessary to adjust thrust. Such thrust adjustments can increase the noise impact in some area below the flight track. It has also been shown that glide slopes greater than 3-degrees can greatly reduce the area of significant noise impact for approach conditions because of the greater

altitude above every point on the ground track and less thrust needed further away from the airport. These types of operations can not be handled during busy periods by the current ATM system, but automated advisory tools developed by the NASA Aviation System Capacity Program are being deployed by the FAA that will allow this in the future. As a consequence, DGPS coupled with CNS systems with automated thrust management could provide significant noise impact reduction during landing operations without increased pilot workload.

The above measures decrease noise exposures for areas away from the immediate airport environs; other operational measures can provide decreased exposure from ground operations near the airport. Automated scheduling of engine startup and gate departure could reduce total engine-on taxi and waiting time as well as reduce the number of times engine power has to be increased to move up one position in a departure queue. Automated scheduling could also provide significant fuel savings and reduced emissions.

Refinement and integration of DGPS, ATM and CNS systems with high fidelity aircraft noise exposure and minimization models, figure 10, could provide for real-time noise management. Such an integrated management system could accommodate changing weather conditions, such as wind shifts and temperature-altitude profiles, which affect noise propagation and areas exposed. Also it would be possible for such a dynamic system to accommodate shifts in population distribution based on work/home schedules and even daily/weekly changes in land use for schools and churches.

## 5 Future challenges

The development of noise reduction technology is a long-term process and therefore one that needs to be undertaken well before the technology is critically needed. Introduction of new technology into the commercial transport fleet in numbers sufficient to benefit the overall aviation system noise impact is also a long-term

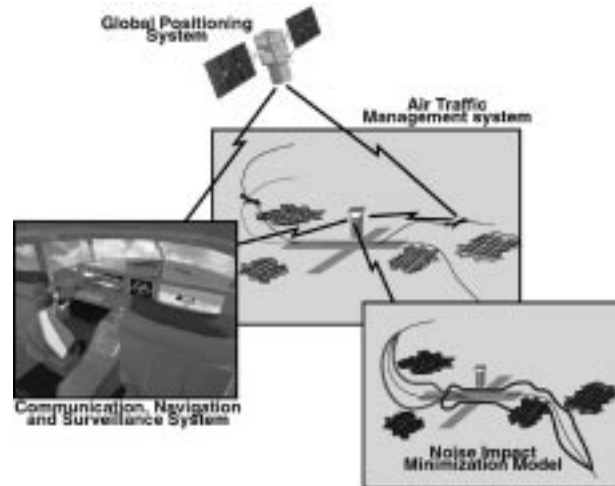


Figure 10. Conceptual real-time noise impact management system.

process involving engineering development, production, and incorporation into the world's fleet. NASA's AST Noise Reduction program efforts will terminate at the end of 2001 and it appears that the objective of developing technology for a 10 dB reduction in subsonic transport noise will be met. Because of the time necessary for the introduction of this new technology into the world's aircraft fleet and the anticipated 3–8% growth in passenger and cargo operations well into the 21st Century, these noise reduction technologies will barely maintain a constant world aircraft noise impact until about 2020 to 2030. After that time increased operations will cause the total impact to increase. Additional noise reduction will therefore be necessary to meet the expected increase in public interest and sensitivity to noise. NASA has begun planning with the FAA, industry, universities and environmental interest groups for a new noise reduction initiative under NASA's Environmental Compatibility noise goal. That goal is to reduce the perceived noise levels of future aircraft by a factor of two within 10 years and by a factor of 4 within 25 years. These translate into noise reductions of 10 dB and 20 dB relative to new aircraft introduced into the fleet in 1997. These reductions will not be totally sufficient to make aircraft noise inaudible in most communities.



However, the reductions should be sufficient to permit the containment, within most airport boundaries, of noise exposures in excess of day-night average sound level (DNL) 55dB. This community noise exposure level has been deemed by the US Environmental Protection Agency as the level "requisite to protect the public health and welfare with an adequate margin of safety." An example is shown in figure 11 of the DNL 55dB contour for a major U. S. airport with traffic growth projected to the year 2005. Additional contours are shown for 5dB reduction increments. As shown a 20dB reduction is sufficient to reduce the contour area so that it is contained within the airport boundary. It is anticipated that if aircraft noise can continue to be reduced so that there is no objectionable exposure outside airport boundaries, noise will no longer be a limit to the growth of the world's air transportation system.

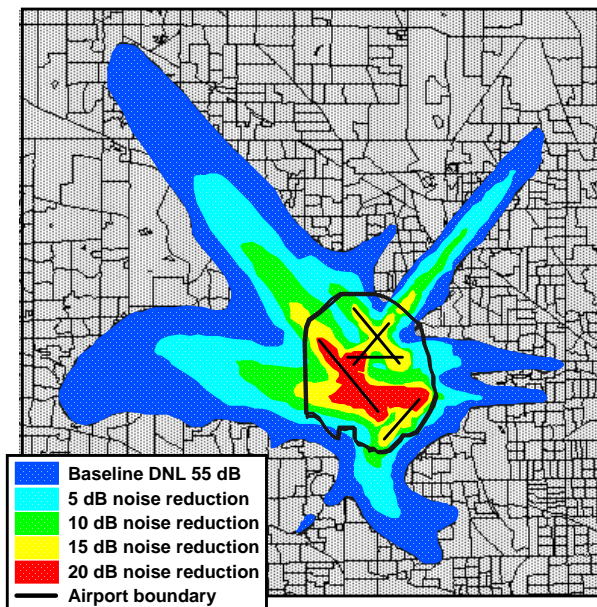


Figure 11. DNL 55dB noise contours for major U.S. airport projected to 2005 showing areas for various levels of noise impact reduction.

Because of the logarithmic relationship for summing the components within the noise of an aircraft and the nearly equal contribution from jet noise, fan noise, and airframe noise, future noise reduction will require that similar reductions will have to be made in all three

sources. The goal of 20 dB noise reduction in 25 years may require totally new aircraft systems. In one of the concepts for these airplanes, namely the Blended Wing Body, figure 12, engines could be integrated within the upper surface of the airframe. The airframe would inhibit downwardly radiated engine inlet noise and be so aerodynamically clean, during



Figure 12. Blended Wing Body advanced transport airplane concept.

takeoff and landing, that airframe noise would not be a problem.

The major challenge in using operations to reduce aircraft noise is the reduction or elimination of the human factor barriers to automation. Many of the information and control technologies required to achieve operational reductions in aircraft noise are near at hand, however the translation of automation generation information into operator knowledge and awareness requires further development. The operational measures and all hardware and software will have to be demonstrated as safe and effective in simulation, flight, and actual air traffic trials to ensure their acceptance.

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